

Navigational Safety in the Suez Canal: HFACS-PV Analysis of Human-Organizational Factors and Environmental Risks with Comparative Insights

Süveyş Kanalı'nda Seyir Güvenliği: İnsan-Örgütsel Faktörler ve Çevresel Risklerin HFACS-PV Analizi ile Karşılaştırmalı İnceleme

Türk Denizcilik ve Deniz Bilimleri Dergisi

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ABSTRACT

Narrow waterways are among the most congested maritime areas and are frequently associated with high incidences of marine accidents. Despite being an artificial canal with mandatory pilotage, the Suez Canal poses a significant threat to maritime trade due to its narrow width and considerable length. Any accident in the canal can disrupt global trade for days. This study aims to identify Human and Organizational Factors (HOFs) and operational conditions (environmental factors) contributing to accidents in the Suez Canal. A total of 47 reported maritime accidents between 2000 and 2023 were analyzed using the Human Factors Analysis and Classification System for Passenger Vessels (HFACS-PV) model. Additionally, the spatial distribution of these accidents was visualized via Tableau, and comparisons were made with other major narrow waterways. According to the analysis, 89% of accident causes were attributed to human and organizational errors, while 11% were due to operational conditions. The most common causes were unsafe acts, precondition for unsafe acts particularly mental health issues and unsafe supervision. Accidents were predominantly concentrated near the northern & southern entrances of canal and the Ismailia region, where vessels have limited maneuverability. Compared to other strategic waterways, the Suez Canal has relatively fewer accidents and collisions; however, groundings are the most common. Moreover, container ships were found to be at higher risk due to the canal's structure and traffic density. Unlike the Turkish Straits, where older vessels are often involved, the involvement of modern ships in Suez Canal accidents underscores the critical role of human and operational failures.

Keywords: Narrow waterway, Suez Canal, Marine accident, HFACS-PV, Human and Organizational Factors (HOFs)

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ÖZET

Dar su yolları, deniz trafiğinin en yoğun olduğu bölgeler arasında yer almakta olup, deniz kazalarının yüksek sıklıkla görüldüğü alanlar olarak bilinmektedir. Zorunlu kılavuzluk hizmetlerinin uygulanmasına rağmen yapay bir kanal olan Süveyş Kanalı, dar yapısı ve önemli uzunluğu nedeniyle deniz taşımacılığı açısından ciddi bir tehdit oluşturmaktadır. Kanalda meydana gelebilecek herhangi bir kaza, küresel ticarete günlerce sürebilecek aksamalara neden olabilmektedir. Bu çalışmanın temel amacı, Süveyş Kanalı'nda meydana gelen deniz kazalarına neden olan İnsan ve Örgütsel Faktörleri (HOFs) ile operasyonel koşulları (çevresel etkenler) belirlemektir. Bu kapsamda, 2000-2023 yılları arasında bildirilen toplam 47 deniz kazası, Yolcu Gemileri için İnsan Faktörleri Analizi ve Sınıflandırma Sistemi (HFACS-PV) modeli kullanılarak analiz edilmiştir. Ayrıca, bu kazaların mekânsal dağılımı Tableau yazılımı aracılığıyla görselleştirilmiş ve diğer önemli dar su yollarıyla karşılaştırmalar yapılmıştır. Analiz sonucunda, kazaların %89'unun insan ve örgütsel hatalardan, %11'inin ise operasyonel koşullardan kaynaklandığı belirlenmiştir. En yaygın nedenler, güvensiz davranışlar, bu davranışların ön koşulları özellikle ruh sağlığına ilişkin sorunlar ve yetersiz denetimdir. Kazalar, çoğunlukla kanalın kuzey & güney girişleri ile manevra kabiliyetinin sınırlı olduğu İsmailiye bölgesinde yoğunlaşmaktadır. Diğer stratejik su yollarıyla karşılaştırıldığında, Süveyş Kanalı'nda görece daha az kaza ve çarpışma yaşanmakta, ancak karaya oturma olayları en sık görülen kaza türü olarak öne çıkmaktadır. Kanalın yapısal özellikleri ve yoğun trafiği, özellikle konteyner gemileri için riski artırmaktadır. Türk Boğazları'nda daha çok yaşlı gemiler kazalara karışırken, Süveyş Kanalı'ndaki kazalarda modern gemilerin yer alması, insan hataları ve operasyonel yetersizliklerin belirleyici rolünü ortaya koymaktadır.

Anahtar sözcükler: Dar kanal, Süveyş Kanalı, Deniz kazası, HFACS-PV, İnsan ve Organizasyonel Faktörler (HOFs)

1. INTRODUCTION

Narrow waterways are complex maritime areas that pose a high risk to maritime activities (Squire, 2003; Bateman *et al.*, 2007; Ulusçu *et al.*, 2009; Huang *et al.*, 2013). These areas contain numerous threats to navigational safety due to limited maneuverability, heavy traffic, strong currents, and adverse environmental conditions (Köse *et al.*, 2003; Başar, 2010; Uğurlu *et al.*, 2013). Straits, in particular, are among the busiest strategic passages for maritime traffic because they provide intercontinental connections and serve as access points for many inland seas to the high seas (Arslan and Turan, 2009; Aydogdu, 2014; Kaptan, 2022). In the event of an accident, the consequences can be felt at both regional and global levels.

Despite recent advancements in maritime technologies and the implementation of international safety regulations (such as those established by the International Maritime Organization), marine accidents continue to

occur in narrow waterways (Celik and Cebi, 2009; Uğurlu *et al.*, 2015; Macrae, 2009; Akhtar *et al.*, 2014). According to data from the European Maritime Safety Agency (EMSA, 2021), approximately 3000 marine accidents were recorded annually between 2015 and 2020, with only minor reductions not exceeding 7% over the years. These statistics indicate that the effectiveness of current safety measures remains limited and requires reassessment (Schröder-Hinrichs *et al.*, 2012; Chauvin *et al.*, 2013; Uğurlu *et al.*, 2020).

The most common types of accidents in narrow waterways include collisions, contacts, groundings, and sinkings (Martins and Maturana, 2010; Chauvin *et al.*, 2013; Graziano *et al.*, 2016; Zacccone and Martelli, 2020). The occurrence of these accidents is typically directly associated with the narrow structure of the channels, high traffic volume, and challenging environmental conditions (Squire, 2003; Aydogdu *et al.*, 2012). In this context, traffic separation schemes, pilotage services, and vessel traffic services (VTS) are employed as key measures to enhance

navigational safety (Uğurlu *et al.*, 2016). However, despite these practices, operational factors such as local maritime traffic, currents, sharp turns, environmental light pollution and inadequate anchorage areas continue to increase the risk of accidents (Köse *et al.*, 2003; Başar, 2010; Uğurlu *et al.*, 2013).

Marine accidents occurring in narrow waterways have extensive economic, environmental, and social implications. For instance, the Ever Given accident in the Suez Canal in 2021 resulted in a six-day disruption of canal traffic, significantly impacting global trade. The economic losses caused by the accident were estimated to be in the billions of dollars (Allianz, 2021).

The Suez Canal is a strategic artificial waterway that connects the Mediterranean Sea to the Red Sea and separates the continents of Africa and Asia. Opened in 1869 and currently under the

control of Egypt, the canal was constructed at sea level and holds vital importance for global maritime transportation due to its position along the shortest and most economical route between Europe and Asia (Shibasaki *et al.*, 2017; SCA, 2025b).

The canal, approximately 194 kilometers long, forms one of the longest uninterrupted artificial sea passages in the world. Vessel passage is organized between Port Said in the north and Port Suez in the south, based on a convoy system. The canal has an average depth of up to 24 meters and can accommodate vessels with drafts exceeding 15.24 meters. However, technical parameters such as vessel beam, draft, weather conditions, and recommended transit speeds play a critical role in determining transit eligibility (United Kingdom Hydrographic Office, 2020; SCA, 2025b).

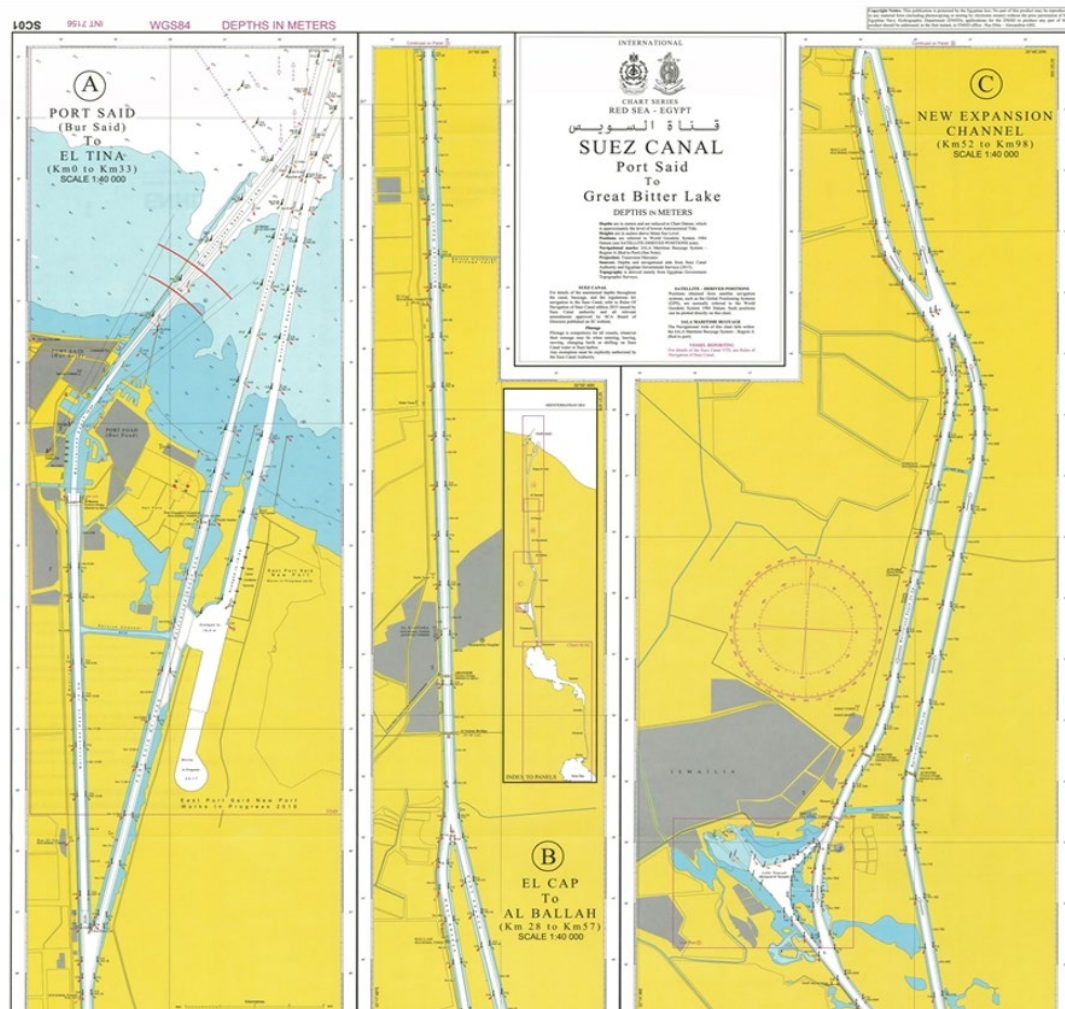


Figure 1. Suez Canal chart (UKHO, 2020)

In response to the growing volume of maritime trade, the "New Suez Canal" project was launched in 2015 to enhance the canal's capacity and reduce transit times. Constructed parallel to certain sections of the existing canal, the new 72-kilometer-long route enables two-way vessel traffic, reducing the transit time from 18 hours to 11 hours and the waiting time from 8–11 hours to as little as 3 hours. This improvement has the potential to increase the canal's daily capacity to approximately 97 vessels (SCA, 2025b).

By providing substantial savings in fuel, time, and operational costs compared to the Cape of Good Hope route, approximately 8% of global maritime shipping is conducted via this passage (Elsherbiny *et al.*, 2019). For example, in 2023 alone, a total of 26434 vessels transited the canal, with an average of 72.4 vessel transits recorded per day (SCA, 2025a).

Yet, due to its geopolitical significance and high traffic density, the Suez Canal entails substantial operational and environmental risks. This study analyzes marine accidents in the Suez Canal through a multilayered approach based on human, organizational, and environmental factors, aiming to enhance navigational safety in the region. The Human Factors Analysis and Classification System for Passenger Vessel Accidents (HFACS-PV) framework was employed for the systematic evaluation of accidents, and the spatial distribution of accidents was visualized through a density map. By offering a comparative perspective between the Suez Canal and other major maritime narrow waterways, this research not only identifies the causes of accidents but also questions the adequacy of existing safety systems and provides concrete insights into potential areas for improvement. Thus, it contributes to a holistic understanding of the risks posed by the structural and environmental characteristics of narrow waterways and emphasizes the need for a reassessment of current safety strategies.

Due to the limited number of studies addressing maritime accidents in the Suez Canal in the existing literature, the primary aim of this study is to investigate the underlying causes of marine accidents in the Suez Canal by adopting a comprehensive and multilayered risk analysis approach. Specifically, the study seeks to

identify the dominant human, organizational, and environmental factors contributing to such accidents; to analyze the spatial distribution of accidents along the canal; and to compare the navigational risk profile of the Suez Canal with other major global narrow waterways. Based on these insights, the study further aims to propose targeted and context-specific safety strategies to mitigate identified risks. By addressing these objectives, the research contributes to a deeper understanding of the structural, operational, and human factors that shape maritime safety in one of the world's most critical narrow waterways. Additionally, this study offers a novel contribution by integrating the HFACS-PV framework with spatial accident mapping and comparative benchmarking, thereby providing geographically-targeted insights for effective navigational risk mitigation in the Suez Canal.

2. MATERIALS AND METHODS

This study investigated marine accidents that occurred in the Suez Canal, a major transit route for global shipping, between 2000 and 2023. A total of 19 accident databases were reviewed, through which data on 47 marine accidents that occurred in the Suez Canal were obtained. During the research, accidents occurring in the Suez Canal were examined in detail. The list of databases used for data collection is presented in Table 1.

The primary objective of this research is to enhance navigational safety in the Suez Canal and identify existing risks by thoroughly analyzing marine accidents occurring in this region in terms of human, organizational, and environmental factors. In addition, the study provides a comparative analysis between the Suez Canal and other major global narrow waterways. The HFACS-PV framework was used for systematic analysis of the accidents. This framework identified the causes of the accidents and conducted a multi-layered assessment. Furthermore, an accident density map was created for marine accidents occurring in the Suez Canal, identifying the areas where the accidents were most geographically concentrated. The research is based on a systematic methodology consisting of four main

stages. This methodological process is structured according to the flowchart presented in Figure 2 and explained in detail below.

Table 1. List of marine accident investigation organizations scrutinized in the study

Name of the Organization			Country
Accident Investigation Board			Norway
Norway			
Australian Transport Safety Bureau			Australia
Bahamas Maritime Authority			Bahamas
Bureau of Maritime Casualty Investigation			Germany
Bureau d'enquêtessur les événements de mer			France
Danish Maritime Accident Investigation Board			Denmark
Dutch Safety Board			Netherlands
European Maritime Safety Agency			Portugal
Global Integrated Shipping Information System			IMO
Japan Transport Safety Board			Japan
Marine Accident Investigation Branch			United Kingdom
Marine Casualty Investigation Board			Ireland
Maritime Safety Administration of People's Republic of China			China
National Transportation Safety Committee			Indonesia
Office of the deputy commissioner of maritime affairs			Liberia
Panama Maritime Authority			Panama
Safety Investigation Authority			Finland
Swedish Transport Agency			Sweden
United States National Transportation Safety Board			USA

2.1. Phases of the Study

2.1.1. Compilation of Accident Data

In this study, to create a dataset for maritime casualties occurring in the Suez Canal, various international and national maritime authority databases, including the Global Integrated Shipping Information System (GISIS), were meticulously searched. GISIS, a global maritime accident recording system within the International Maritime Organization (IMO), contains highly detailed information on marine accidents occurring in strategically important narrow waterways like the Suez Canal. In addition to GISIS, complementary information was obtained through the Marine Accident Investigation Branch (MAIB), the Suez Canal Authority (SCA), and relevant academic literature reviews. During the data compilation process, accident records from maritime casualties occurring in the Suez Canal between 2000 and 2023 were reviewed, and only those whose reliability was verified and whose location and accident details could be clearly identified were included in the study. To ensure data reliability, only official reports published by internationally recognized marine accident investigation bodies (e.g., GISIS, SCA, MAIB, NTSB) were considered. Reports were included if they provided verifiable identifiers (e.g., vessel name, IMO number, date), geographic location, and accident details. Cross-validation across sources was conducted to eliminate inconsistencies. Reports with incomplete or conflicting information were excluded.

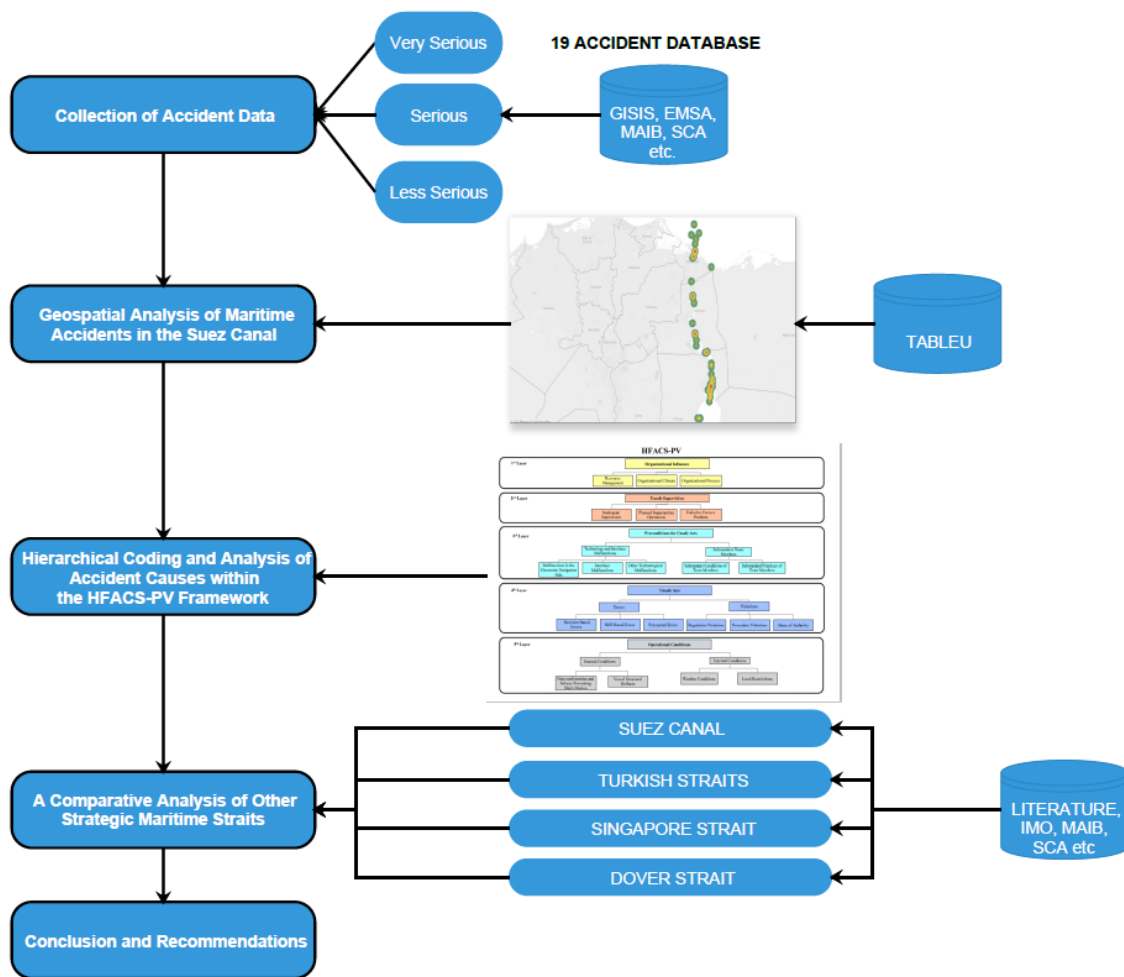


Figure 2. Flow chart

2.1.2. Geographic Visualization

The collected accident data were geolocated and their spatial distribution analyzed using the Tableau software (Tableau, 2025). In this stage, the spatial data related to marine accidents in the Suez Canal were converted into a format compatible with analysis in Tableau. Initially, the coordinate information and other relevant details (e.g., date, vessel type, damage status) of each accident, obtained from the accident databases, were compiled. These data were then converted into a Comma Separated Values (CSV) file, a format supported by Tableau, and the geographic coordinates (latitude and longitude) of each accident were plotted as point data on the map. After the data were imported into Tableau, all accident locations were mapped and visualized along the canal. Attribute information for each

accident point (such as accident type, date, and damage level) was entered through the data table, and the accidents were categorized based on these attributes. For instance, collision accidents were represented in blue, contact accidents in blue, and grounding events in green, each indicated with distinct symbols on the map. This visualization enabled a clear spatial analysis of the concentration of different accident types along various sections of the Suez Canal.

2.1.3. Creating the HFACS-PV Framework

In this study, an analysis framework was created in the analysis of marine accidents occurring in the Suez Canal, taking as reference the HFACS-PV model developed by Uğurlu *et al.* (2018) (Figure 3).

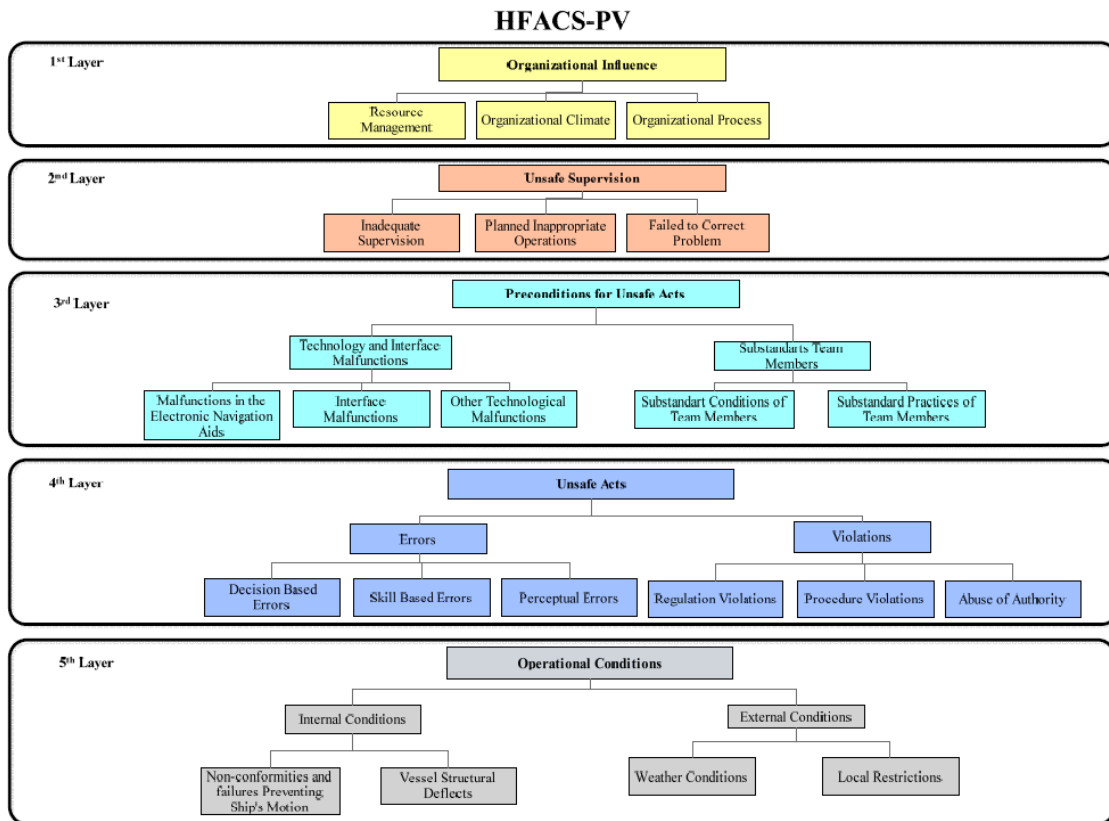


Figure 3. HFACS-PV structure analysis framework

This five-level model is integrated into the study to encompass unsafe acts, organizational influences, unsafe supervision, pre-condition for unsafe acts and environmental factors (operational conditions). The foundation of HFACS lies in the Swiss Cheese Model developed by Reason (1990), which categorizes accident-inducing events across four levels under the headings of latent factors and active failures. According to this model, latent failures such as organizational deficiencies and inadequate supervision can sequentially lead to unsafe actions by operators, ultimately resulting in accidents. Unlike the original structure developed by Shappell and Wiegmann, (1996), the HFACS-PV framework consists of five levels, with the highest level incorporating operational conditions (environmental factors). In this expanded version, environmental conditions are treated as a decisive final stage contributing to accident occurrence (Figure 3). In this study, the occurrence of marine accidents is defined through three main stages: causal factors (including organizational influences,

unsafe supervision, and preconditions for unsafe acts), active causes (unsafe acts), and operational conditions that contribute directly to accident occurrence. Unlike previous studies in the literature, this research treats operational conditions not as preconditions for unsafe acts, but as high-level factors that directly lead to accidents (Uğurlu *et al.*, 2018). This distinction is based on the premise that an unsafe act alone is not sufficient to cause an accident unless accompanied by suitable operational conditions. Moreover, unlike the other levels related to human error, operational conditions often involve factors that are partially or entirely beyond human control (Uğurlu *et al.*, 2020). However, when properly considered in decision-making processes, these factors can contribute to the prevention of accidents (Yildiz *et al.*, 2024). The HFACS-PV framework was originally developed based on accident data from passenger vessels. However, recent studies have demonstrated its applicability across various types of ships and accident scenarios (Uğurlu *et al.*, 2018; Yıldiz *et al.*, 2021; Yıldiz *et al.*, 2024).

The most distinguishing feature of the HFACS-PV structure is its inclusion of Operational Conditions as a separate and final level, which enhances its suitability for maritime contexts beyond passenger vessels. In this study, the HFACS-PV model was applied to a dataset including container ships, bulk carriers, and tankers. The levels and categories under Unsafe Acts and Preconditions for Unsafe Acts were already adapted for maritime-specific conditions in prior research. Furthermore, at least one operational condition was identifiable in each accident report, regardless of vessel type. These observations confirm the model's compatibility with different ship types and support its broader applicability in maritime accident analysis. In this context, accidents that occurred in the Suez Canal were systematically coded within the framework of the HFACS-PV model, and the accident development processes were presented within a hierarchical structure, providing a better understanding.

2.1.4. Comparative Analysis

In the fourth stage of this study, the navigational safety characteristics of the Suez Canal were comprehensively compared with those of other strategic maritime passages, including the Istanbul Strait, the Çanakkale Strait, the Singapore Strait, and the Dover Strait. The comparison considered key parameters such as the natural configuration of the passages, current characteristics, the scope of pilotage services, traffic density, VTS, draft and air draft limitations, as well as accident statistics. This analysis aimed to examine the causes of marine accidents in the Suez Canal within a broader context and to systematically identify the structural and operational factors that contribute to such accidents.

During the comparative analysis process, structural and operational information regarding the Suez Canal and other narrow waterways was collected through an extensive literature review. Data obtained from sources such as GISIS, MAIB, SCA, and various academic publications were systematically compiled to create a comparative table reflecting the technical and operational characteristics of each passage. Through this table, the unique risk factors

associated with each waterway and their impacts on navigational safety were evaluated both visually and analytically. While identifying the strengths and weaknesses of the Suez Canal, the significance of each parameter in terms of navigational safety was analyzed individually. Qualitative data were examined using an interpretive analysis approach and elaborated in the findings section of the study. This process also served as a basis for the development of recommended preventive measures.

3. RESULTS

An examination of the accident dataset used in this study reveals that a total of 47 marine accident reports related to the Suez Canal were identified between 2000 and 2023. This corresponds to an average of approximately two reported marine accidents per year during the specified period. According to vessel traffic data for the Suez Canal, a total of 26434 vessel transits occurred in 2023 alone, which equates to an average of approximately 72.4 transits per day (SCA, 2023). Despite the strategic importance of the canal for global maritime transportation, the number of accessible accident reports remains limited, indicating a relatively low level of data availability for this region. A temporal comparison of accident frequency reveals a 24% increase over time: 21 accidents were recorded between 2000 and 2011, whereas 26 occurred between 2012 and 2023. This trend suggests a gradual rise in accident frequency in recent years, warranting further investigation into evolving risk factors and systemic vulnerabilities within the Suez Canal transit system.

The findings of the study indicate that marine accidents are more concentrated at the entry and exit points of the Suez Canal rather than within the canal itself (Figure 4). Notably, significant clusters of accidents were identified near the northern entrance (around Port Said), the southern exit (around Port of Suez), and the entrance and exit areas of the Great Bitter Lake. Similarly, an increased concentration of accidents was observed in the Ismailia region, particularly in the transitional zone where the waterway narrows and shifts to one-way traffic. These areas are considered critical navigation

segments due to increased demands for traffic control and vessel maneuvering and are regarded

as some of the most operationally complex sections of the canal.

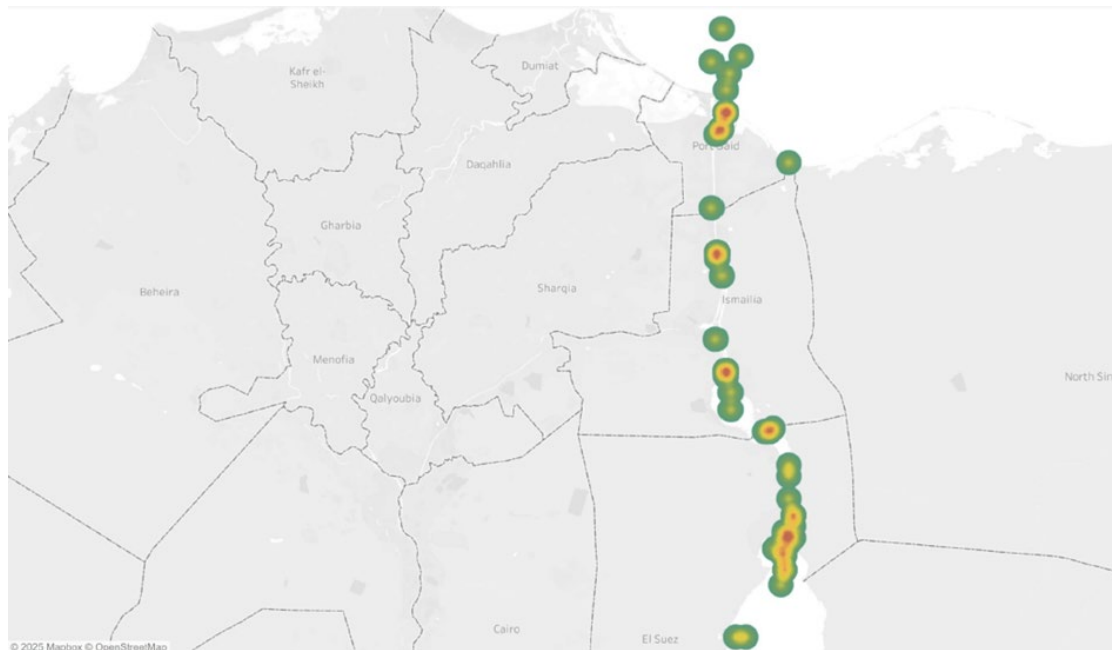


Figure 4. Distribution of accident density in the Suez Canal

An analysis of the distribution of marine accidents in the dataset by vessel type reveals that 32% of the accidents involved container vessels, 26% involved bulk carriers, and 23% occurred with tanker-type vessels. These

findings indicate that marine accidents in the Suez Canal are particularly concentrated among specific vessel types, especially container vessels (Figure 5).

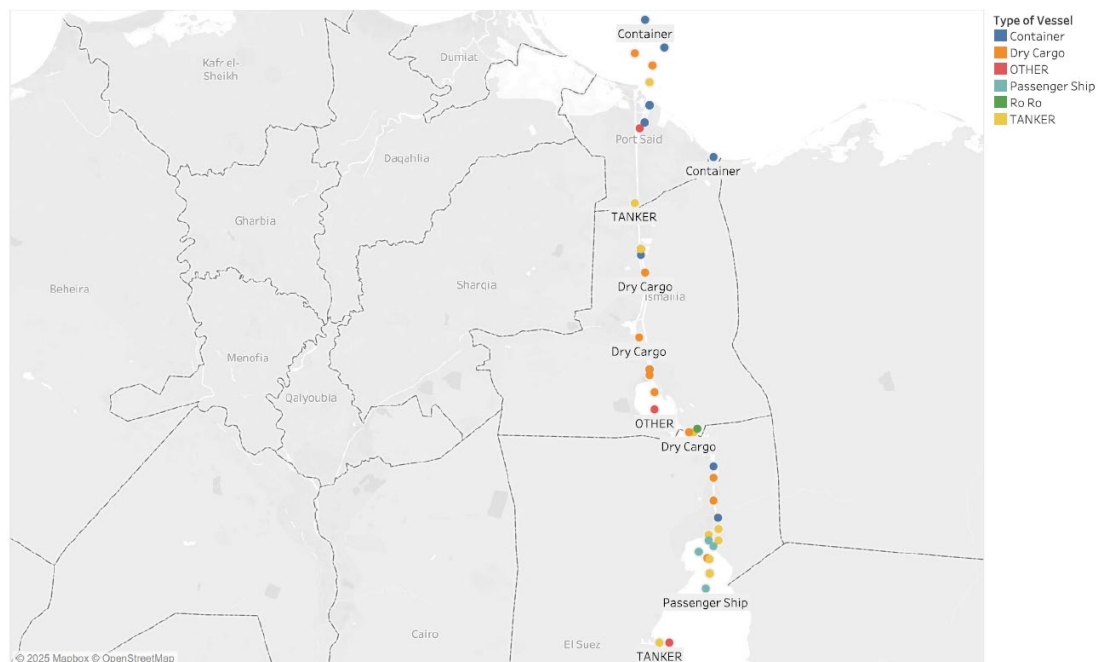


Figure 5. Distribution of accidents in the Suez Canal by type of vessel

An examination of accident severity revealed that a large portion of accidents (79%) were classified as serious accidents, 12% as very serious accidents, and 9% as less serious accidents. Furthermore, when Figure 6 was analyzed for the relationship between accident severities and the geographic locations where the

accidents occurred, no clear pattern was observed. This suggests that different severities can be randomly distributed across different points and regions along the channel, and therefore, certain severities are not concentrated in specific areas.

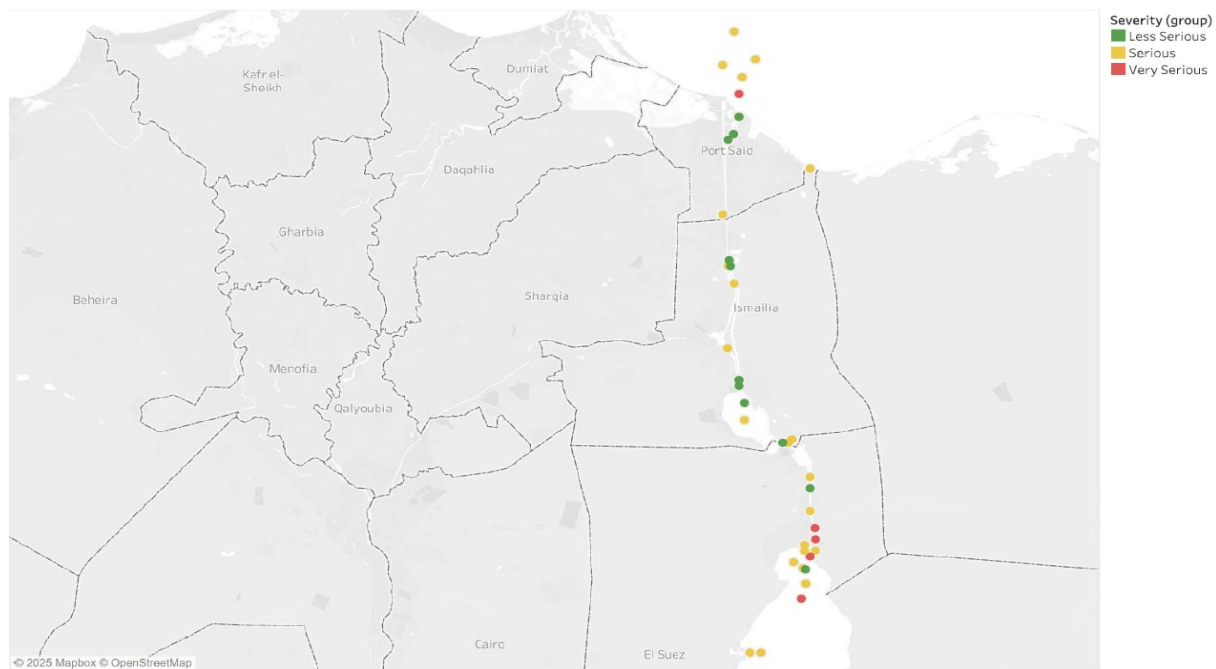


Figure 6. Distribution of accidents in the Suez Canal by severity of accident

An analysis based on accident types revealed that 43% of the accidents involved grounding. This was followed by collision/contact accidents at 32%, fire and explosion at 13%, flooding at 8%, and machinery damage at 4%. As shown in Figure 7, the relationship between accident types and the geographic locations where the accidents

occurred; however, no clear pattern was observed. This finding suggests that different accident types are randomly distributed across various regions along the Suez Canal, and that specific accident types are not concentrated in specific areas.

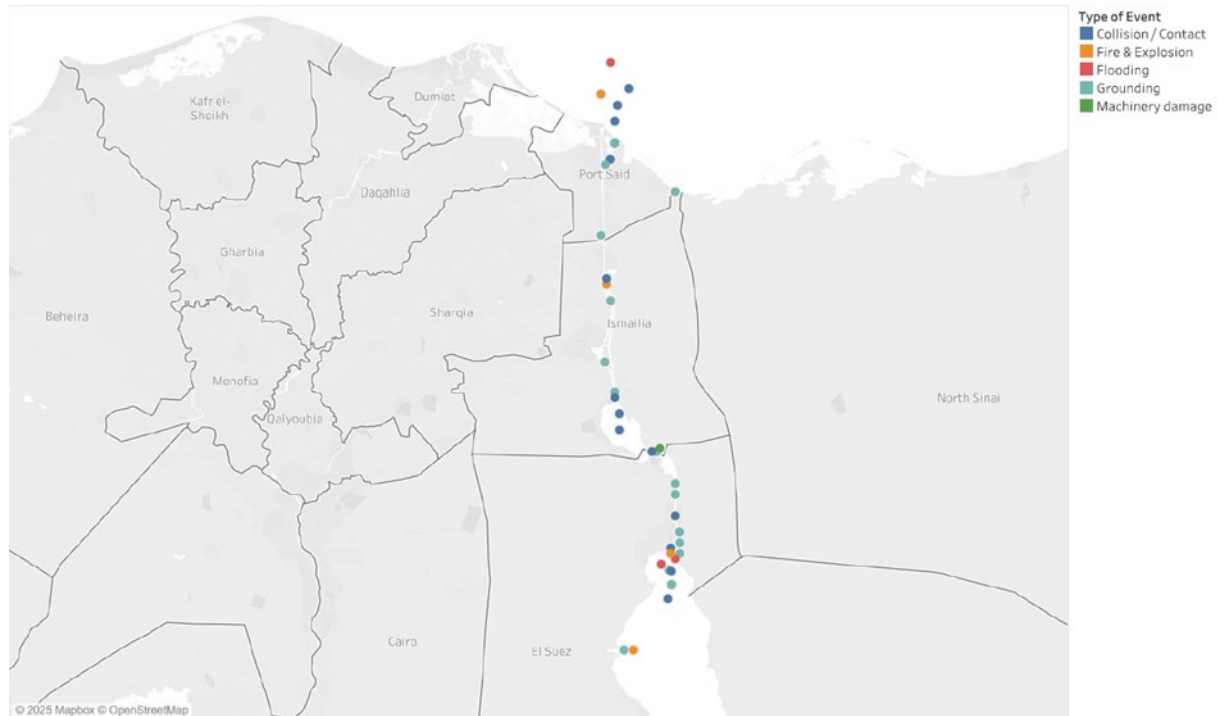


Figure 7. Distribution of accidents in the Suez Canal by type of accident

An analysis of the gross tonnage (GRT) of vessels involved in the accidents revealed that 23% of the accidents were caused by ships with a GRT of less than 10000. The largest proportion of accidents (51%) involved vessels with a GRT between 10000 and 100000, while large vessels with a GRT greater than 100000 accounted for 26% of the cases. These findings indicate that the majority of marine accidents in the Suez Canal were caused by medium and large tonnage vessels. When examining the geographical distribution of accidents in relation to vessel tonnage, it was observed that accidents involving large ships (GRT > 100000) were mostly concentrated at the canal's entry and exit points

or in sections where the waterway narrows and one-way traffic regulations are implemented (Figure 8). In particular, areas such as the Port Said and Suez entrances/exits, as well as the connections to the Great Bitter Lake, pose higher risks for large vessels due to limited maneuvering space, low-speed navigation requirements, and high traffic density. Similarly, the narrow and complex transit sections around Ismailia also emerge as critical risk zones for large tonnage ships. This finding suggests that as vessel tonnage increases, the likelihood of accidents also rises in narrow, congested, or maneuver-intensive sections of the canal.

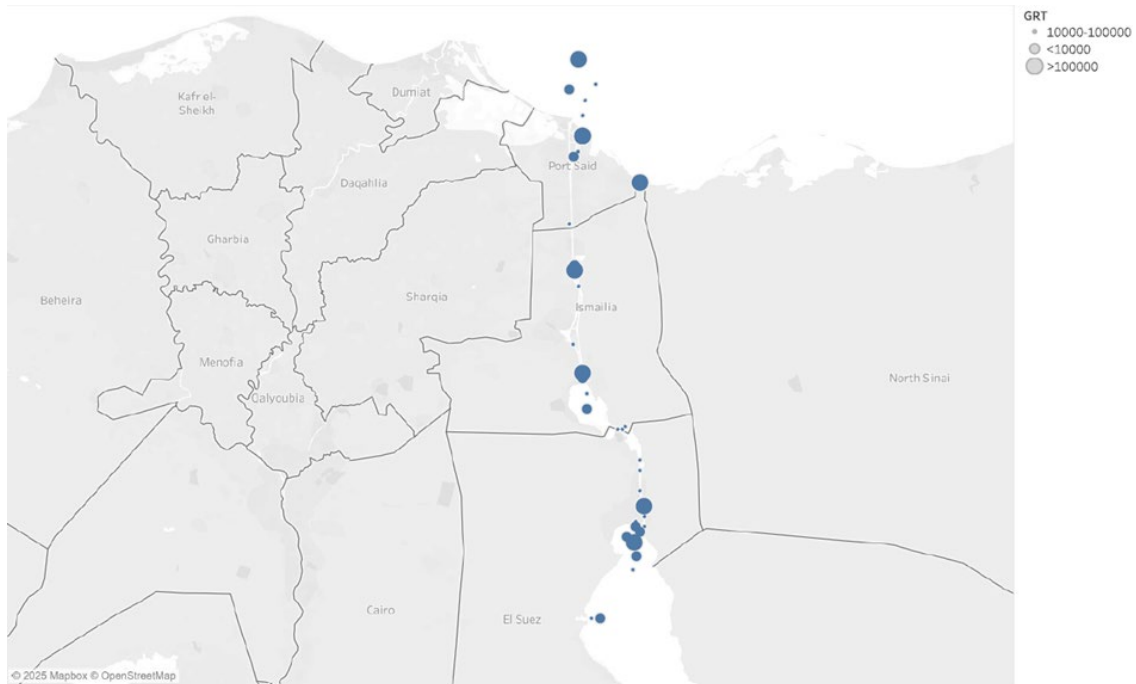


Figure 8. Distribution of accidents in the Suez Canal by vessel GRT

An analysis of the ages of vessels involved in accidents revealed that 49% of the accidents were caused by ships less than 10 years old. Vessels aged between 10 and 20 years accounted for 19% of the accidents, while those over 20 years old were involved in 32% of the cases. This distribution indicates that marine accidents are not limited to older or technically obsolete vessels; on the contrary, relatively new and modern ships also contribute significantly to

accident occurrences. As shown in Figure 9, the relationship between vessel age and the geographical location of accidents was analyzed; however, no clear pattern was observed. This finding suggests that accidents involving vessels of different age groups are randomly distributed along the Suez Canal, and there is no observable concentration of accidents involving ships within a specific age range in particular regions.

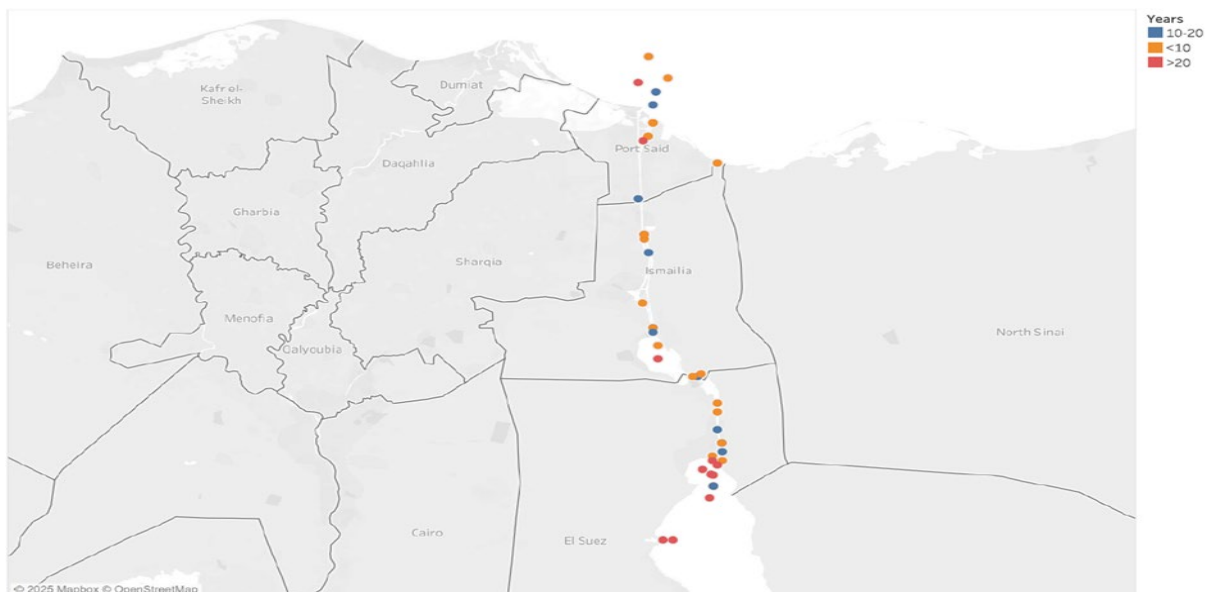


Figure 9. Distribution of accidents in the Suez Canal by vessel age

An analysis of the causes of the 47 marine accident cases examined in this study reveals that 89% of the accidents were attributed to Human and Organizational Factors (HOFs), while 11% were caused by environmental factors. Causes related to HOFs were classified under the categories of organizational influence, preconditions for unsafe acts, unsafe acts, and unsafe supervision, whereas environmentally induced causes were grouped under operational conditions. According to this classification, the most frequently observed causes fell under unsafe acts, accounting for 35% of the cases. This was followed by preconditions for unsafe acts at 27% and unsafe supervision at 17%.

The HFACS classification system categorizes accident-causing factors into two main groups in accordance with Reason's Swiss Cheese Model: latent factors and active failures. In this study, latent failures include deficiencies related to organizational influence, preconditions for unsafe acts, and unsafe supervision. Under active failures, the category of unsafe acts representing direct unsafe behaviors is examined. In addition,

environmental factors referred to as operational conditions represent the internal and external environmental circumstances that increase the likelihood of unsafe acts leading to accidents, thus playing a complementary role in the accident causation process. Active failures are observable and directly influential factors in the development of an accident, whereas latent factors are typically embedded within the deeper layers of the system. These latent factors encompass the structural deficiencies and systemic weaknesses that underlie active errors and are often difficult to detect without in depth analysis.

A detailed analysis of the organizational influence category, which falls under latent failures, reveals that the majority of accidents in this category were primarily caused by deficiencies in resource management (Figure 10). These deficiencies stem from both the inadequate familiarization and preparation of human resources for their duties, as well as from the insufficiency of equipment and facility resources.

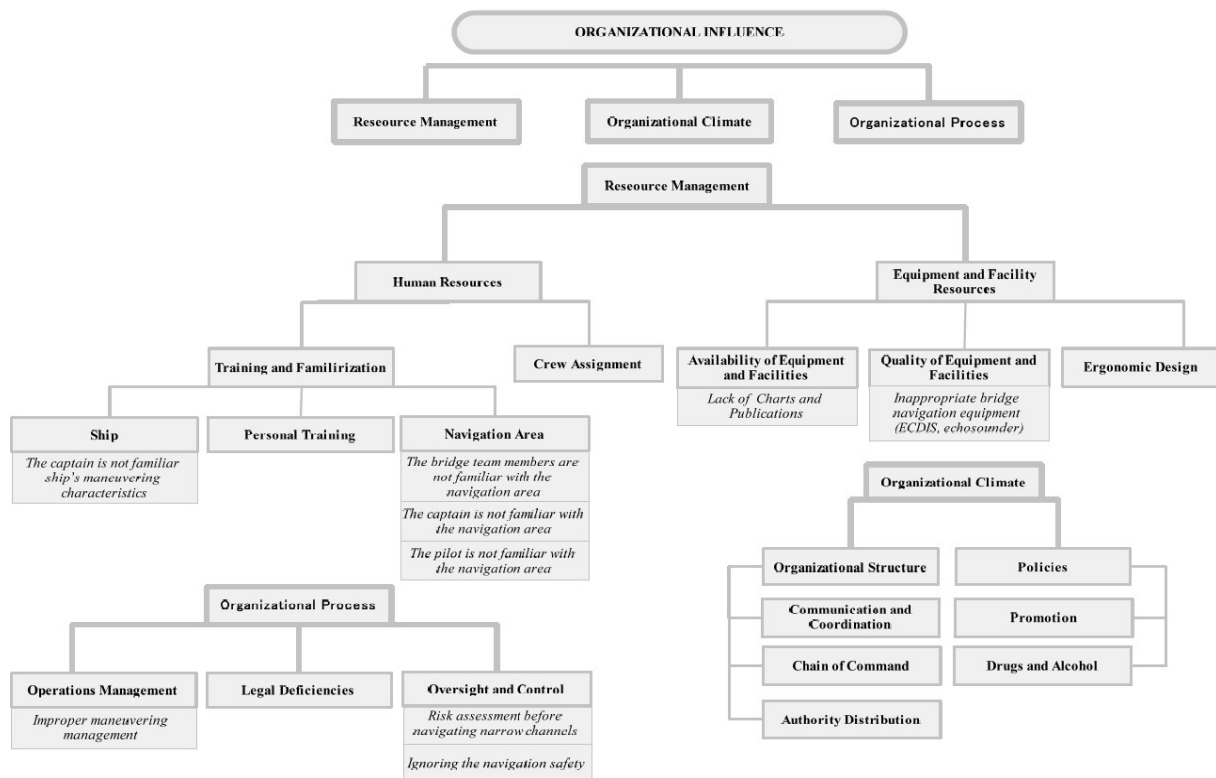


Figure 10. Organizational influence diagram

When examining the unsafe supervision level, the most significant cause of accidents in this category was determined to be insufficient supervision (Figure 11). This factor was followed by planned inappropriate operations. A detailed examination of the Precondition for

Unsafe Acts factor revealed that the most significant factor leading to accidents was crew mental health issues (Figure 12). This was followed by Improper Management Activities and Lack of Communication and Coordination.

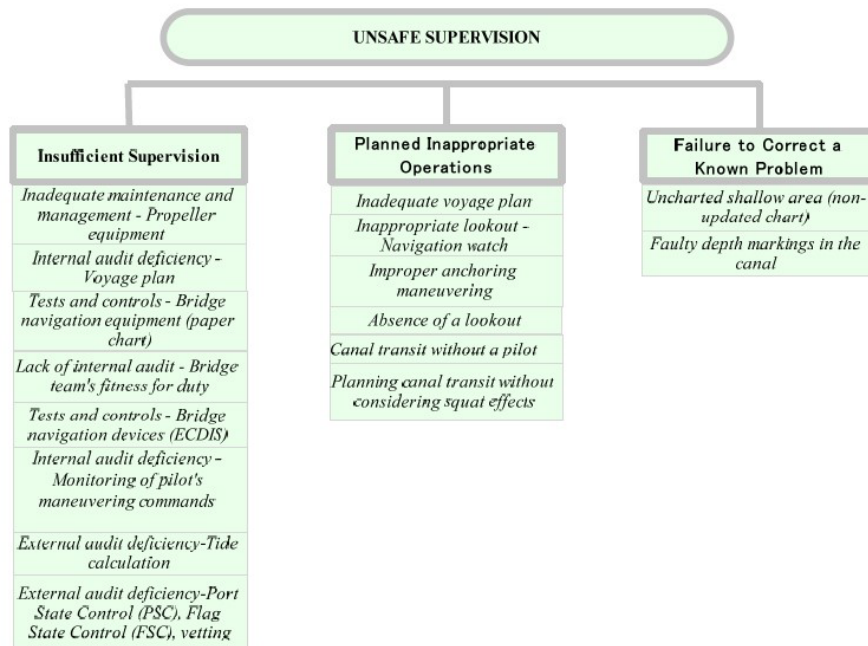


Figure 11. Unsafe supervision diagram

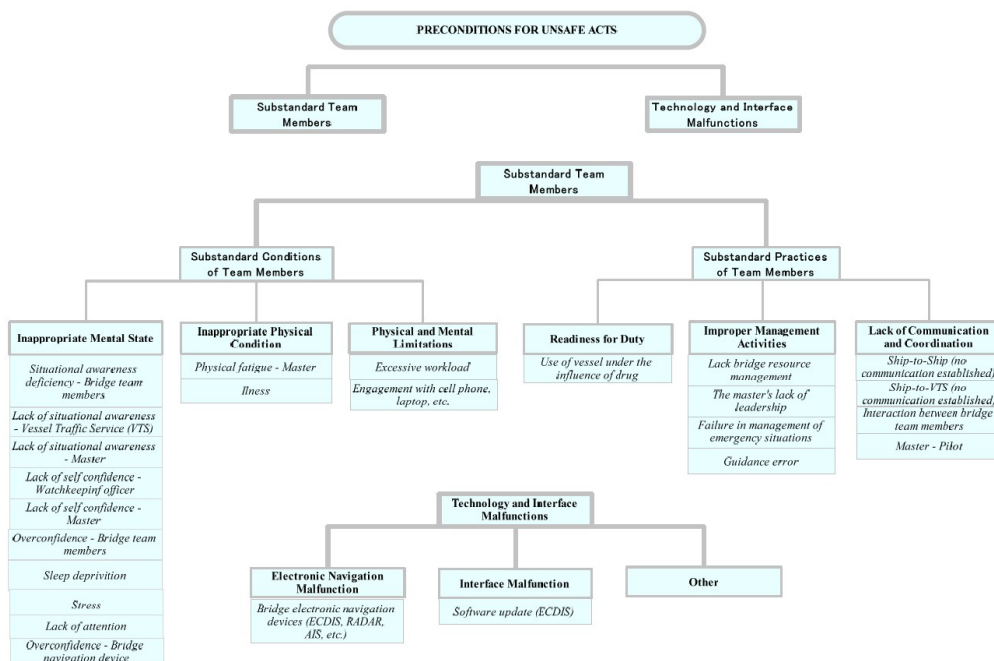


Figure 12. Precondition for Unsafe Acts Diagram

In the analysis of the unsafe acts category, it was determined that the causes of accidents due to

errors and violations were seen at similar rates in the accidents in the Suez Canal (Figure 13).

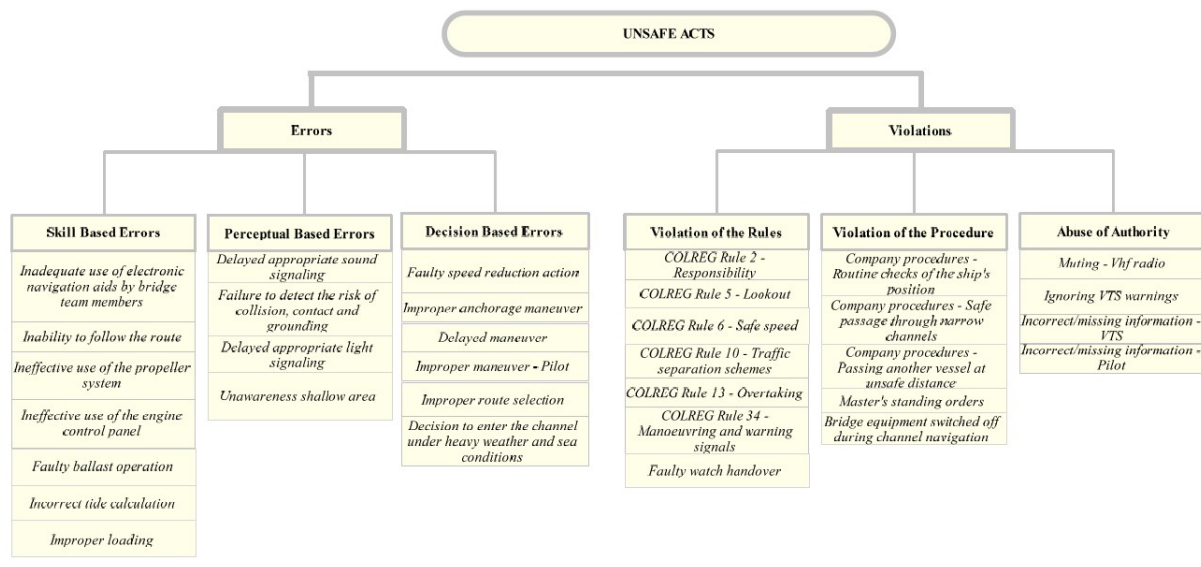


Figure 13. Unsafe acts diagram

When the operational condition category, evaluated within the scope of environmental factors, was examined, it was determined that the most important cause of accidents in this group

was internal conditions, defined as ship equipment failures (Figure 14). This factor was followed by weather conditions.

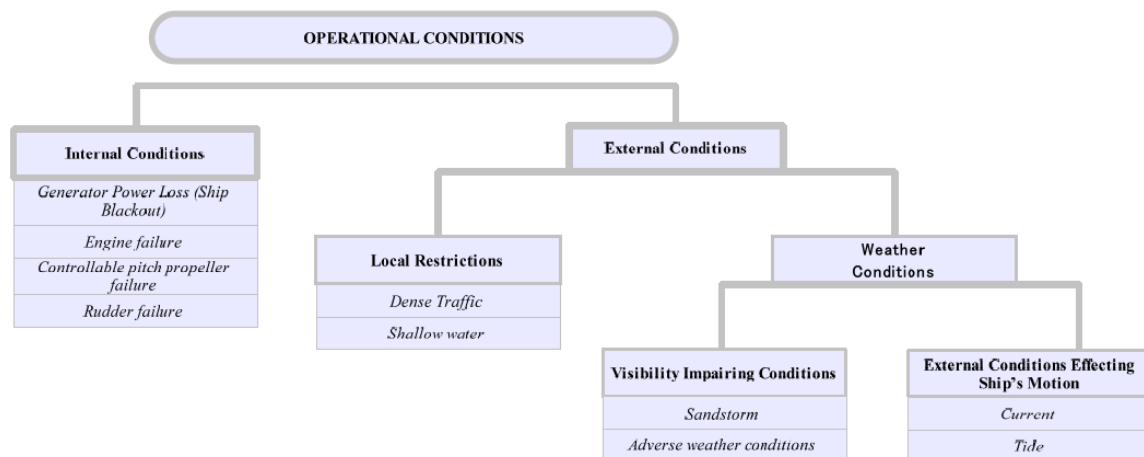


Figure 14. Operational conditions diagram

Table 2. Characteristics of Major Global Canals and Straits (Bayazit et al., 2020; Ece et al., 2020; EMSA, 2018; Kuleyin and Aytekin, 2015; Loughney et al., 2022; SCA, 2023; SCA, 2025b Tonoğlu et al., 2022; Yildiz et al., 2022a; Yildiz et al., 2022b; Yildiz et al., 2024)

Criteria	Istanbul Strait	Çanakkale Strait	Suez Canal	Singapore Strait	Dover Strait
Location	Connects the Black Sea to the Sea of Marmara	Connects the Sea of Marmara to the Aegean Sea	Connects the Mediterranean Sea to the Red Sea	Connects the Malacca Strait to the South China Sea	Connects the English Channel to the North Sea
Natural Structure	Length is 16.6 miles. It is a narrow waterways with sharp turns. Shoals up to 17m in some locations.	Length is 37.8 miles. Steep shores, high depth. Sharp turns. Minimum depth 22.5m.	Length is 105 miles. Artificial canal. No sharp turns. Width 205–225m, depth 24m.	Length is 57 miles. Shortest route between Indian and Pacific Oceans. Sharp turns exist.	Approximately 100 miles long. Narrow structure and meteorological conditions make navigation risky.
Currents	Strong surface and bottom currents. Seasonal currents reach up to 6–7 knots in some areas.	Strong surface and bottom currents. Seasonal currents reach up to 1.5–4 knots.	Low current regime due to minimal elevation difference. Currents 1–3 knots.	Normal flow 0.3–0.5 knots; tidal currents 1.6–6.2 knots.	Strong tidal currents. Tidal waves create current speeds up to 5–6 knots.
Vessel Traffic Services (VTS)	Available. Includes 4 sectors (Türkeli, Kandilli, Kadıköy, Marmara). Helps reduce risks for traffic order.	Available. Includes 3 sectors (Gelibolu, Nara, Kumkale). Helps reduce risks for traffic order.	Available. But no sector division. Single VTS center serves whole canal.	Available. 7–9 sector VTS centers. Jurisdiction under Klang and Johor VTS.	Available. No sector division. Single center serves whole channel.
Pilotage	Pilotage service is available but not mandatory. Pilot captains increase safety.	Pilotage service is available but not mandatory. Presence of pilot captain increases safety.	Pilotage is mandatory and significantly contributes to canal safety.	Pilotage not mandatory. For Very Large Crude Carriers (VLCCs) over 15m draft, pilotage recommended.	Pilotage is not mandatory.
Local Traffic	Especially heavy in the Kadıköy sector despite being present in all sectors.	Heavy in Nara sector, except Kumkale.	Almost no local traffic; not a significant obstacle.	Local fishing boats pose threats to large vessels.	Ferries, private boats, and traffic congestion between UK and France present risks.
Traffic Density	Approx. 45000 vessel transits annually.		Approx. 26434 vessel transits annually.	Approx. 75000 vessel transits annually.	Approx. 150000 vessel transits annually.
Draft and Air Draft Restriction	Because the Turkish Straits are natural straits and have suitable depths, they are capable of navigating even today's large ships. The structure of the existing bridges also does not impose any significant restrictions on air draft.		The Suez Canal, an artificial waterway, currently serves vessels with a maximum draft of 66 feet. The suspension bridge and two overhead power lines spanning the canal do not pose significant navigational obstacles due to their structural characteristics.	There are transit restrictions in the canal for VLCCs and vessels with a draft exceeding 15 meters. In particular, the area near Batu Berhanti poses a navigational risk due to its depth of less than 21 meters and a channel width of only 1.2 nautical miles.	The average depth is 46 meters, and there are no air draft restrictions.
Width	The narrowest point is 698 meters wide.	The narrowest point is 797 meters wide.	205-225 meters	16 km. The narrowest point is 1.2 km wide.	34 km
Accident Frequency (Transits per Accident)	Approximately one accident occurs for every 2,547 transits.		Approximately one accident occurs for every 13487 transits.	Approximately one accident occurs for every 1957 transits.	Approximately one accident occurs for every 380 transits.

Similar to other straits, the Suez Canal functions as an intercontinental transit corridor by connecting two distinct seas the Mediterranean Sea and the Red Sea. In addition to offering a significant distance advantage in global maritime trade, the canal contributes to shorter voyage durations, reduced fuel consumption, and lower operational costs. In this context, the Suez Canal is considered to possess not only geographical, but also global economic and logistical strategic significance. The canal is the only artificially constructed strait among the straits included in the comparison and is also the longest (105 miles) (SCA, 2025a). Due to the minimal elevation difference between the Red Sea and the Mediterranean, the canal's current regime is significantly weaker compared to other straits (1-3 knots). Like many narrow waterways, the canal is equipped with a VTS system, which supports navigational safety. However, unlike the others, pilotage is mandatory in the Suez Canal (SCA, 2025c) an important factor that helps reduce the risk of human error-related accidents. This requirement is considered one of the key reasons for the relatively low number of accidents recorded in the canal. From the perspective of local maritime traffic, the Suez Canal is largely isolated from the heavy local vessel activity observed in straits such as Istanbul, Çanakkale, Singapore, and Dover. Therefore, there are no significant local navigational obstacles affecting traffic flow within the canal. Additionally, when compared with the other straits analyzed, the Suez Canal handles a relatively lower volume of vessel transits (72.4 vessels per day). Nonetheless, as an artificial waterway, the canal is subject to structural constraints, particularly in terms of its limited width (205-225 m) and maximum allowable draft (20.12 m) (SCA, 2025b). When accident statistics are examined, it is observed that the Suez Canal experiences fewer marine accidents than the other passages included in the study.

Table 2 presents a comparative overview of key characteristics of several prominent strategic canals and straits around the world. The table compares the Suez Canal, Istanbul Strait, Çanakkale Strait, Singapore Strait, and Dover Strait in terms of various operational and physical parameters, including geographical

location, natural or artificial formation, current conditions, implementation of VTS, mandatory pilotage, presence of local traffic, traffic density, draft and air draft limitations, transit width, and number of accidents. These waterways are of significant importance to global maritime trade and serve as critical transit corridors connecting different seas. The Istanbul Strait links the Black Sea to the Sea of Marmara; the Çanakkale Strait connects the Sea of Marmara to the Aegean Sea; the Suez Canal connects the Mediterranean Sea to the Red Sea; the Singapore Strait links the Strait of Malacca to the South China Sea; and the Dover Strait serves as a strategic corridor between the English Channel and the North Sea. An analysis of some marine accidents occurring in the Suez Canal reveals that a lack of experience is a significant risk factor. One of the incidents investigated was a fire accident. In this accident, it was determined that the ship's crew acted inadequately and unprepared during firefighting, leading to delays in determining the source of the fire, which significantly increased material damage and made it difficult to control the fire (Isle of Man Ship Registry, 2015). Another incident involved a grounding accident. In this accident, two pilots left the ship after the ship reached the Suez Canal exit. However, the new pilots who were supposed to replace them did not board the ship, despite compliance with canal regulations. The previous pilots left the ship after informing the ship's captain of the route and the passage. Shortly thereafter, the ship ran aground due to failure to recognize the shallows at the canal exit. The accident report stated that the captain did not have adequate control of the ship and entered the canal at a speed exceeding the maximum permitted draft (Panama Maritime Authority, 2011). When all these factors are evaluated together, it is noteworthy that the basis of the accidents is the lack of sufficient experience of the ship crew and the operational errors resulting from this deficiency.

A significant proportion of accidents occurring in the Suez Canal are primarily influenced by current and shallow water conditions. In particular, the currents prevalent near the southern entrance of the canal pose a serious threat to navigational safety. For instance, in one of the examined accidents, the vessel's bow

suddenly veered to port due to strong currents at the southern exit, resulting in a loss of control and subsequent grounding (Maritime Affairs Republic of Liberia, 2007). Furthermore, many grounding accidents are attributed to the failure to detect shallow water areas in a timely manner. Certain accident reports emphasize the risk associated with vessels deviating from the traffic separation scheme, especially in the vicinity of the southern anchorage area located beyond the southern exit of the canal. It has been suggested that some of the shallow patches in this area may not be charted or that outdated nautical charts may have been in use onboard, thus contributing to the oversight of these hazards. Moreover, similar environmental conditions were influential in the Ever Given accident of 2021, which caused significant disruptions to global maritime trade. Shortly after entering the canal, the vessel lost control and ran aground due to intense currents, strong winds, and a sandstorm. This accident further underscores the critical role that environmental factors and the natural configuration of the canal play in marine accidents.

In some accidents that occurred in the Suez Canal, physical and mental limitations, particularly distraction and neglect of duty, appear to have directly contributed to the accident. In one of the cases examined, it was determined that the first officer, due to personal issues, failed to focus sufficiently on his bridge duties during his watch. During that watch, the first officer's constant communication via the bridge computer due to family matters led to his neglect of his lookout duties. Furthermore, the absence of an additional lookout on the bridge, other than the first officer, significantly reduced situational awareness. Warnings issued by the VTS went unnoticed due to this inattention, and as a result, the ship ran aground off the Gulf of Suez. This accident clearly demonstrates that psychological and cognitive load can reach levels that can negatively impact navigational safety. Table 2 provides important information by comparing the characteristics of various canals and straits around the world. Among the regions examined, pilotage is only mandatory in the Suez Canal. This suggests that the presence of pilots with extensive knowledge of the region can

significantly reduce the risk of accidents. While local maritime traffic poses a significant risk in the Istanbul, Çanakkale, Singapore, and Dover Straits, this risk is almost negligible in the Suez Canal. This may be due to the Suez Canal being an artificial canal. In terms of channel width, the Istanbul Strait is the second narrowest waterway after the Suez Canal. The narrowness of the waterways is a significant factor in the frequent grounding accidents in both the Suez Canal and the Istanbul Strait.

4. DISCUSSIONS

When examining the frequency of marine accidents in the Suez Canal, a comparative assessment with other narrow waterways of global significance provides a more meaningful perspective. According to the EMSA (2018) report, an annual average of 45000 vessel transits occurred through the Turkish Straits (Istanbul and Çanakkale) between 2011 and 2017, during which a total of 106 marine accidents were recorded. This corresponds to approximately one accident per 2547 transits. In contrast, the Suez Canal saw 26434 vessel transits in 2023 (SCA, 2023), and only 47 marine accidents were reported between 2000 and 2023 equating to one accident per 13487 transits. In the Singapore Strait, an average of 75000 vessel transits occurs annually, with 230 marine accidents reported (Yildiz *et al.*, 2022b), corresponding to one accident per 1957 transits. Meanwhile, the English Canal experiences approximately 150000 annual transits, and between 2011 and 2017, a total of 2370 marine accidents were recorded (Yildiz *et al.*, 2022a), resulting in one accident per 380 transits. When these data are evaluated, it is seen that the accident frequency in the Suez Canal is quite low compared to other passages with heavy maritime traffic.

The findings of the present study indicate that 89% of marine accidents in the Suez Canal are attributable to HOFs, while the remaining 11% result from environmental causes. This finding demonstrates that human errors are the primary determinant of marine accidents in the Suez Canal. Similarly, an analysis conducted by Loughney *et al.* (2022) in the Strait of Dover found that 77% of grounding accidents and 79%

of collision and contact accidents were related to HOFs. The share of environmental factors remains relatively low in both regions, indicating that human and organizational factors are common and dominant causes of accidents in narrow waterways. An examination of environmental factors revealed that vessels under 10 years of age were most frequently involved in marine accidents in both the Dover Canal and the Suez Canal. Container ships have the highest passage frequency in both the Dover and Suez Canals. In the Istanbul Strait, they rank second (Yildiz *et al.*, 2022a).

An analysis of the underlying causes of accidents reveals that the most frequently observed factor in the Suez Canal is unsafe acts, accounting for 35% of accidents. This is followed by preconditions for unsafe acts at 27%, and unsafe supervision at 17%. In the Dover Strait, unsafe acts also emerge as the most common cause, constituting 38% of both grounding and collision/contact accidents. In grounding cases, unsafe acts are followed by operational conditions at 23% and preconditions for unsafe acts at 21%. For collision accidents, the next most frequent causes are preconditions for unsafe acts at 23% and operational conditions at 21%. These findings indicate that individual errors are the primary contributors to accidents in both regions, while secondary causes vary depending on the operational and environmental context. In this context, the prominence of mental health issues among crew members as preconditions for unsafe acts may be attributed to specific operational stressors inherent to the Suez Canal. The convoy-based transit system, which permits vessels to transit in groups at designated times, creates long waiting periods both prior to and during passage. These delays can generate cumulative psychological strain and anxiety, especially for crews under pressure to meet tight delivery schedules. Furthermore, the narrow and linear geometry of the canal demands constant vigilance and precise navigation, contributing to high cognitive workload for bridge teams. Limited anchorage and maneuvering options further amplify the stress, as there is little margin for error in the event of mechanical or navigational issues. These environmental and organizational stressors may lead to fatigue,

reduced attention, and impaired decision-making, thus increasing the likelihood of unsafe acts. Similarly, previous studies have highlighted that human factors such as lack of training, fatigue, carelessness, and risky behaviors are among the primary causes of onboard occupational accidents, further emphasizing the critical role of individual-level factors in maritime safety (Özdemir *et al.*, 2018). Given the dominance of individual-level errors in both regions, it is clear that raising the safety awareness of personnel in the maritime sector is extremely important to effectively prevent such accidents (Altinpinar and Basar, 2018). Among the 47 marine accident reports examined, it was identified that 5 vessels were not accompanied by a pilot at the time of the accident. However, for the remaining cases, while pilot presence was noted, the reports did not provide sufficient detail to determine whether pilot error was a contributing factor.

A comparison with Yildiz *et al.*, (2022a) reveals structural and operational differences in accident patterns across the Suez, Istanbul, and Dover Straits. In terms of spatial distribution, accidents in the Istanbul Strait are predominantly concentrated in anchorage areas, while in the Dover Strait, accidents are more frequently observed in the northern traffic separation scheme, particularly on the English (Dover) side. In the Suez Canal, accident clusters are notably observed at key entry and exit points such as Port Said, Suez Port, the Great Bitter Lake, and Ismailia, as well as in narrow passage sections of the canal. This pattern indicates that in both the Dover Strait and Suez Canal, accidents are not limited to static zones but also occur with greater frequency in dynamic areas where maneuverability and traffic control are critically important.

In terms of accident types, collisions are the most common type of accident in the Singapore Strait (90%) (Yildiz *et al.*, 2022b), the Istanbul Strait (60%), and the Dover Strait (52.9%) (Yildiz *et al.*, 2022a), while this rate drops to 32% in the Suez Canal, with groundings being the most common type at 43%. Similarly, Kilic and Akdamar, (2020) found groundings to be the most common accident type in the Çanakkale Strait at 35%. This difference suggests that the

linear and narrow structure of the Suez Canal increases navigational difficulties and highlights the risk of grounding. The distribution of accidents by vessel type shows significant variation across regions. In the Istanbul Strait, 72.1% of the vessels involved in accidents are dry cargo ships, whereas in the Dover Strait, 38.2% of accidents involve "other types" of vessels such as Ro-Ro and passenger ships (Yildiz *et al.*, 2022a). In contrast, in the Singapore Strait, dry cargo ships are the most frequently involved vessel type, accounting for 33% of accidents (Yildiz *et al.*, 2022b). In this study, it was found that 32% of the accidents in the Suez Canal involved container ships. According to Suez Canal Authority (SCA, 2023) statistics, the vessels transiting the canal consist of 32% tankers, 27% bulk carriers, and 22% container ships. This means that although container ships rank third in terms of total transits, they represent the vessel type with the highest accident involvement rate, suggesting that container ships carry higher risk factors. Container ships are generally very large and high-structured vessels. These physical characteristics can make them difficult to maneuver in confined waterways like the Suez Canal, thereby increasing the likelihood of accidents. Furthermore, the Suez Canal is a heavily trafficked passage. The large size of container ships can pose greater risks within this dense traffic environment. Additionally, container shipping is typically time-sensitive, which may compel such vessels to complete their transit as quickly as possible. This pressure to maintain speed represents another factor that may elevate accident risk.

In terms of accident severity, 91.3% and 52.9% of accidents occurring in the Istanbul Strait and Dover Strait, respectively, were classified as serious (Yildiz *et al.*, 2022a), while this rate was 79% in the Suez Canal. An examination of accident trends based on ship age revealed that vessels younger than 10 years were involved in only 18.8% of accidents in the Istanbul Strait, compared to 52.9% in the Dover Strait (Yildiz *et al.*, 2022a) and 49% in the Suez Canal. This reflects the influence of the more modern fleet structure using the Dover Strait and Suez Canal routes but also highlights the vulnerability of

younger vessels to operational errors and the importance of human factors, in addition to technical equipment. All these comparative data clearly demonstrate that not only structural factors such as ship type, age, or traffic density, but also operational variables such as geographical features, navigation characteristics, traffic management, and environmental conditions play a decisive role in the occurrence of marine accidents.

5. CONCLUSIONS

Safe maritime transportation in the Suez Canal is critical to the sustainability of global trade. The grounding of the container ship Ever Given in 2021, which halted traffic in the canal for several days, clearly demonstrated the impact of navigational safety in this route on the global economy. Therefore, accurately identifying the threats to navigational safety in the Suez Canal is crucial. This study conducted a multidimensional analysis of marine accidents in the Suez Canal, encompassing human, organizational, and environmental factors. The causes of accidents were systematically examined using HFACS-PV, and the key risk factors affecting navigational safety in the region were identified. Furthermore, the Suez Canal was compared to other critical narrow waterways for global maritime transport to assess the region's unique operational challenges. A marine accident map, created with the support of a Tabelau, visualized the spatial distribution of accidents and identified critical points of concentration.

This study concluded that the Suez Canal has significantly fewer ship accidents than the Dover Canal, the Istanbul Strait, and the Singapore Strait. The fact that the canal is an artificial passage and that passages are mandatory with the presence of pilots may have contributed to the low number of accidents.

It has been determined that accidents in the Suez Canal are generally concentrated in areas where traffic control and maneuvering requirements are increased. The northern entrance (Port Said), the southern exit (Port Suez), the entry and exit points of the Great Bitter Lake, and the Ismailia area stand out as the most operationally complex areas of the canal and the most critical in terms

of navigational safety. This clearly demonstrates that these areas are priority risk areas for navigational safety. Therefore, the need for new practices to more effectively regulate ship traffic in these areas is clear. The inadequacy of current traffic planning can be considered one of the primary causes of accidents. In this context, reviewing and developing traffic management strategies to mitigate risk is crucial.

This study reveals that marine accidents occurring in the Suez Canal are largely due to human and organizational factors. Deficiencies in resource management, inadequate supervision, crew mental health issues, and inadequate preparedness for duty are among the primary causes of these accidents. The similar prevalence of errors and violations underscores the importance of systemic adjustments as well as individual performance. Furthermore, disruptions in critical operational processes, such as pilot changes, as well as individual factors such as inadequate crew preparation and distraction, play a decisive role in the occurrence of accidents. While the impact of environmental factors is limited, currents, shoals, and equipment failures increase the structural risks of the canal. The findings highlight the need for a holistic approach to simultaneously address human performance, organizational structures, and environmental conditions to enhance navigational safety in the Suez Canal.

In addition, this study extends previous applications of the HFACS-PV framework by integrating spatial analytics, thus enabling region-specific accident risk mapping in artificial narrow waterways—an approach that represents a methodological advancement not widely explored in prior research.

To mitigate the identified risks and enhance navigational safety in the Suez Canal, several practical measures are recommended. These include: (i) the enhancement of Vessel Traffic Services (VTS) monitoring and the integration of automated alert systems at the northern and southern entrances; (ii) the improvement of scheduling practices and rest protocols for pilots to reduce fatigue-related errors; (iii) the implementation of mandatory pre-entry briefings for high-risk vessels, such as container ships exceeding 100000 GRT; and (iv) the introduction

of comprehensive crew well-being programs that address both physical and mental health, particularly during extended waiting periods and high-stress transit operations. These measures aim to strengthen operational coordination, reduce human error, and improve overall traffic management in the most critical zones of the canal.

AUTHORSHIP STATEMENT

CONTRIBUTION

İbrahim Burak BAŞKAN: Methodology, Validation, Formal Analysis, Resources, Data Curation, Software, Visualization.

Fatih SANA: Validation, Formal Analysis, Writing - Original Draft, Software, Visualization.

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CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

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